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Carbon dynamics in the Amazonian Basin: Integration of eddy covariance and ecophysiological data with a land surface model

Bassil El-Masri*, Rahul Barman, Prasanth Meiyappan, Yang Song, Miaoling Liang[1], Atul K. Jain

Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, Urbana, IL, United States

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ABSTRACT

Information contained in eddy covariance flux tower data has multiple uses for the development and application of global land surface models, such as evaluation/validation, calibration and process parameterization for carbon stocks and fluxes. In this study, we combine Large Scale Biosphere–Atmosphere Experiment in Amazonia (LBA) project data collected from a network of eddy covariance flux towers deployed across the Amazonian basin to improve the carbon stocks and flux estimated by a land surface model, the Integrated Science Assessment Model (ISAM). We evaluate the key model parameters for carbon allocation factors, maintenance respiration as well as the autotrophic respiration using the LBA site measurements. Our model results show that the total biomass ranges from 0.7 kg C m^{-2} yr^{-1} for the pasture site to 20.8 kg C m^{-2} yr^{-1} for the forest site. The ISAM estimates for GPP and NPP are well within the uncertainty range of the site measurement data. Also, the results revealed that all, but one forest site have lower net primary productivity (NPP) to gross primary productivity (GPP) ratio (NPP/GPP = 0.4 compared to the savanna and the pasture sites (NPP/GPP = 0.5). This is because savanna and the pasture sites experienced the longest dry season and plants growing in such environmental conditions have stronger efficiency to store carbon compared to forests. The forest evergreen site (Km67) has a higher measured NPP/GPP ratio (0.5), because of higher carbon accumulation. Soil carbon is lowest for the pasture site (Km77) (7.2 kg C m^{-2} yr^{-1}) and highest for the forest site (Km34) (12.8 kg C m^{-2} yr^{-1}). The model results suggest that all the forest sites are a net sink for atmospheric CO_2, while the savanna (PDG) and pasture (FNS) sites are neutral and another pasture site (Km77) is net source for atmospheric CO_2. Meanwhile, the model results highlight the importance of the LBA site data to improve the model performance for the tropical Amazon region. The study also suggest the need for a network of long-term monitoring plans to measure changes in the vegetation and soil carbon biomass at the local and regional levels. Such programs will be necessary to make reliable global carbon emissions estimates.

1. Introduction

The Amazonian forests play a key role in the global carbon cycle, contributing to about 30% of the global biomass and terrestrial productivity (Beer et al., 2010; Houghton et al., 2001; Malhi and Grace, 2000; Melillo et al., 1996). The increase in air temperature, and shift in precipitation intensity and duration due to climate change has altered carbon fluxes from the Amazonian rainforests (Botta et al., 2002). Some studies suggested that CO_2 fertilization might have led to an increase in carbon uptake by about 3 Pg C yr^{-1} in undisturbed forests (Houghton et al., 2000; Saleska et al., 2003). In contrast, ecosystem modeling studies suggest that due to climate variability, the Amazon basin is a net source during the drier and warmer El Niño and net sink during the wetter and cooler La Niña cycle (Asner et al., 2000; Baker et al., 2008; Foley et al., 2002; Potter et al., 2001, 2009; Tian et al., 1998).

The landscape of Amazon is also changing dramatically due to human activities. Over the past few decades, increased demand for agricultural products due to rising population led to massive deforestation rates (Asner et al., 2005; Moran, 1993; Morton et al., 2005; Skole and Tucker, 1993). Deforestation can also lead to degradation in the ecosystem services such as lower water quality, spread of infectious diseases, and increases in tree mortality through an increase in fire frequency (Foley et al., 2007). It is expected that the rates of deforestation will continue to increase as more urbanization expands to the core of the forest (Laurance et al., 2001). Such

* Corresponding author. Tel.: +1 2173001842.
E-mail addresses: belmasri@illinois.edu (B. El-Masri), rbarman2@illinois.edu (R. Barman), meiyapp2@illinois.edu (P. Meiyappan), song81@illinois.edu (Y. Song), mliang@Princeton.edu (M. Liang), jain1@illinois.edu (A.K. Jain).
[1] Current address: Civil and Environmental Engineering, Princeton University, Princeton, NJ, United States.

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Notation

Veg_frct	vegetation cover fraction
Cn_{leaf}	carbon:nitrogen ratio for the leaves
Cn_{stem}	carbon:nitrogen ratio for the stem
Cn_{roots}	carbon:nitrogen ratio for the roots
V_{cmax}	maximum carboxylation rate at 25 °C
k_n	light extinction coefficient
k_{leaf}	base respiration rate for leaves
K_{stem}	base respiration rate for stem
K_{root}	base respiration rate for roots
ω	allocation parameter
ε_{leaf}	parameter controlling allocation to leaves
ε_{stem}	parameter controlling allocation to stem
ε_{root}	parameter controlling allocation to roots
k	allocation parameter
Y_{leaf}	leaf life span
r_{wmax}	maximum drought leaf loss rate
r_{tmax}	maximum cold leaf loss rate
b_w	parameter for leaf loss (drought)
b_t	parameter for leaf loss (cold)
T_{cold}	temperature threshold for leaf loss because of cold stess
Y_{stem}	stem turnover rate
Y_{froot}	fine root turnover rate
Y_{croot}	coarse root turnover rate
R_{leaf}	maintenance respiration for leaves
R_{stem}	maintenance respiration for stem
R_{root}	maintenance respiration for roots
R_{mtotal}	total maintenance respiration
R_G	growth respiration
R_{auto}	autotrophic respiration
C_{leaf}	leaf carbon
C_{stem}	stem carbon
C_{root}	root carbon
Ø	leaf phonological status defined as the current fraction of maximum LAI
gt	temperature dependent function
T_{veg}	vegetation temperature (°C)
T_{soil}	soil temperature (°C)
GPP	gross primary productivity
NPP	net primary productivity
$Allo\_fact_{leaf}$	allocation factor for leaves
$Allo\_fact_{stem}$	allocation factor for stem
$Allo\_fact_{root}$	allocation factor for roots
L	light availability factor
ws	water stress factor
LAI	leaf area index
LAI_max	biome specific maximum LAI
T_r	root temperature
Bio_tr	biome specific root temperature
Bio_trmin	biome specific minimum root temperature
daylen	biome specific day length

rapid changes in land use will lead to a massive carbon release from the soils, and vegetation speeding up the climate change. The forests and woodlands (e.g. Savannas) also exchange large amounts of water and energy with the atmosphere, and the loss of large areas of Amazonian forest due to land-use and land-use change could impact local and regional climates (Ramankutty et al., 2007).

Given the importance of the Amazon basin toward the regional and global budgets of carbon, energy, and water fluxes (Andreae et al., 2002; Costa and Foley, 2000; Foley et al., 2007; Werth and Avissar, 2002), an international scientific endeavor headed by Brazil had led to the establishment of a Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) (Avissar and Nobre, 2002) The main science objective of the LBA project is to understand the interactions between the atmosphere and climate change variability, in the Amazonian terrestrial ecosystems (Avissar et al., 2002). Such observational data from the LBA sites can substantially improve the understanding of the carbon exchange between the terrestrial ecosystem and the atmosphere and the detection of deficiencies in the land surface models (LSMs). For instance, several studies using LSMs have predicted a decline in topical forest water and carbon fluxes during the dry season (Botta et al., 2002; Tian et al., 1998), while site measurements suggest the opposite (Von Randow et al., 2004; Saleska et al., 2003). Without constraining the models using site observations, LSMs would perhaps underestimate the global carbon fluxes and fail to detect the carbon dynamic of the tropical forests (Saleska et al., 2003). Therefore, these observations are crucial for the improvement of LSMs. Since climate change and variability affect the global terrestrial biogeophysical and biogeochemical cycles (Davidson et al., 2012; Malhi et al., 2008), LSMs with their complex and detailed biogeochemical and biogeophysical processes are important tools to gain better understanding of the interactions between the Amazon basin terrestrial ecosystem and environmental change.

In this paper, we take advantage of observational data from flux tower sites to present a methodology to calibrate and improve an LSM by identifying and modifying the key model carbon schemes in order to enhance the vegetation and the soil carbon estimates. We use the Integrated Science Assessment Model (ISAM) to show the feasibility of our approach and its relevance to other LSMs. This paper extends upon previous modeling application of the ISAM (Jain et al., 2009; Yang et al., 2009) by detailing the carbon dynamics of the LBA sites representing forests, savannas, and pastures ecosystems of the Amazonian basin. Notably, the version of ISAM used in this study contains detailed biogeophysical processes (Song et al., 2013) coupled into the biogeochemical component of ISAM. This extended version of the model is used to examine the interannual variability of carbon fluxes (Gross primary production (GPP), net primary production (NPP), autotrophic and heterotrophic respirations) and above and below ground biomass of eight LBA study sites in the Amazon basin (Table 1). The objective has been achieved by comparing the model estimated carbon fluxes with eight LBA project flux towers measurements. The study is designed to: (1) provide a brief description of the carbon dynamics of ISAM, (2) calibrate the model parameters using site data, (3) evaluate the model performance by comparing the model calculated carbon fluxes with eddy covariance flux towers measurements, and (4) evaluate the model estimated soil and vegetation carbon with published studies.

2. Methodology

2.1. ISAM description

The ISAM is one of the 23 models participating in the LBA project to study the responses of Amazon basin terrestrial ecosystems to environmental factors. The ISAM is a land surface model that is applied to examine the impacts of changing CO_2 in the atmosphere, fire, and land use change on terrestrial ecosystems functions (Jain et al., 1996; Jain and Yang, 2005; Jain et al., 2006). ISAM has also been used to describe the dynamic of the terrestrial biosphere carbon (Jain et al., 1996; Jain and Yang, 2005) and nitrogen (Jain et al., 2009; Yang et al., 2009). It was a part of the IPCC assessments of future climate change scenarios (Schimel et al., 1996; Prentice et al., 2001). The latest version of the ISAM has also participated in the Modeling and Synthesis Thematic Data Center (MAST-DC) study as